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Commensurability effects in magnetic properties of superconducting Nb thin films with periodic submicrometric pores

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ABSTRACT

Pinning properties in 100 nm thick continuous and porous superconducting Nb films are examined by ac susceptibility and dc magnetization measurements. The Nb film was deposited on a smooth Si substrate, while the porous film, Nb_P, was deposited on an anodized Al oxide substrate. Pores or “antidots” 40 nm in diameter, 100 nm apart, form a triangular array. The porous film presents commensurate or matching field effects for applied magnetic fields where the magnetic flux threading each unit cell is an integer number of the flux quantum, where ac shielding capability and dc diamagnetic magnetization show an abrupt increase. The response to ac fields as a function of temperature and dc field provided a way to determine that Nb_P sample has higher pinning than the continuous one, and that T_C suppression due to fluxoid quantization is not relevant for the investigated temperature range.

1. Introduction

The interaction between elastic media and periodic pinning potentials [1] is present in many well-known systems as for example charge and spin density waves, absorbed atomic layers in periodic substrates and superconducting vortices in samples with artificial periodic pinning centers. This last system is particularly convenient for studying these interactions because the relative spacing between vortices and pinning sites can be easily varied by changing the magnitude of the applied magnetic field. Additionally, the characteristic length scales that are relevant in pinning interactions can be modified by changing the temperature, making it possible to “tune” different pinning regimes. As a consequence, superconducting films with periodic arrays of artificial pinning centers have attracted a great deal of attention in recent years. Thin superconducting films, either patterned with square or triangular arrays of pores or “antidots” [2], or deposited on self-assembled porous substrates [3], have been used as model systems.

The pinning mechanism by “antidots” has mainly two different origins. One is vortex core pinning, known as coherence length or $\xi(T)$ pinning, and arises from the core term in the vortex free energy that is suppressed when the flux line is located on the defect. The second is electromagnetic pinning (known as penetration depth or $\lambda(T)$ pinning) where the distortion of currents or fields by the defects leads to a variation in the free energy that is minimized for vortices standing on circular or cylindrical defects [4] and dominates for larger antidots of size comparable to λ.

Arrays of defects lead to commensurate effects for applied fields where N vortices (each carrying one flux quantum $\phi_0 = hc/2e$) occupy one cell of the pinning lattice. For these “matching” fields critical current density, J_C, is enhanced. In cases in which the pinning lattice parameter, d, is comparable to the antidot diameter D, i.e. when $d - D < \xi(T)$, matching effects also occur for $N = p/q$ a rational number [5], and the system resembles a superconducting network. It is therefore expected that at temperatures very near the zero field critical temperature T_{C0}, every sample would approximate to a network [3], where the periodic suppression of $T_C(H)$ is consistent with Little and Parks type of effect [6]. In these cases matching effects are not really due to an increase in J_C at commensurate fields, but to a decrease in J_C for fields that do not “match” with the pinning array, although this is still an open question.

For samples with low matching fields (~10 Oe) [2], i.e. samples where antidots are separated in the micrometer scale, the increase in J_C for a wide temperature range has been described in detail. Recently, in samples comparable to the ones used in this paper, commensurate effects at matching fields ~2000 Oe have been shown to be related to Little and Parks effect [3]. However, experiments were performed very near the critical temperature, T_{C0}. It is expected that far from T_C pinning effects have to become dominant.

In this work we present ac susceptibility, $\chi_{ac}(H,T)$, measurements in Nb thin films with a triangular array of antidots

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separated by submicrometric distances, below the critical temperature of the film. J_C is determined and effective pinning studied. We compare results for a reference continuous Nb film and discuss the dominant regime at the investigated temperature and field ranges. The reduction of T_{C0} [7,8] in films with antidots, presumably related to proximity effect with impurities in the porous substrate, corrugation or stress of the superconducting film, has to be considered and data at the same reduced temperatures compared. Magnetization hysteresis loops are also presented, and show that matching field effects are robust, although relaxed J_C results smaller than in ac measurements.

2. Experimental

Self-ordered porous alumina masks were fabricated by a two step anodization of Al films (AAO) grown on semiconducting substrates as described elsewhere [9]. Fig. 1 shows an SEM image of the 100 nm thick porous Nb film, Nb_P, sputtered on the AAO substrate resulting with pores of diameter $D \sim 40$ nm separated at mean distance $d \sim 100$ nm in a triangular array. A reference Nb film, also 100 nm thick, was deposited on a smooth Si substrate.

The ac susceptibility, χ_{ac}, and the dc magnetization hysteresis curves, $M(H,T)$, were measured using a QD MPMS XL 7 T. Both dc and ac magnetic fields, H and h, were applied perpendicular to the films surface. The reference Nb film (typical dimensions $2 \times 3\,\text{mm}^2 \times 100\,\text{nm}$) has an onset temperature $T_{C0} = 8.25\,\text{K} \pm 0.05\,\text{K}$ defined as the onset of the ac susceptibility transition at $H = 0$, for $h = 1$ Oe and $f = 995$ Hz, where the 10−90% transition width $\Delta T_C \approx 1.3$ K. The porous film of similar dimensions, has a zero field critical temperature onset $T_{C0} = 7.25\,\text{K} \pm 0.05\,\text{K}$ [7,8] and the 10−90% transition width is also $\Delta T_C \approx 1.2$ K. For the triangular array of antidots, the calculated matching field is $H_1 = (2/\sqrt{3})(\phi_0/d^2) = 2310$ Oe.

3. Results and discussion

Fig. 2 shows $\chi_{ac}(T)$ for the continuous Nb film in full symbols and for the porous Nb film, Nb_P, in open symbols as a function of reduced temperature $t = T/T_{C0}$, for different values of applied H. In all cases ac field amplitude was $h = 1$ Oe and frequency $f = 997$ Hz. Shielding capability for zero applied field is similar in both samples as a function of reduced temperature. However, it is strongly suppressed by dc field in the Nb film as compared to the sample with antidots, although both samples are in the critical state regime with losses $\chi_{ac}(T) \approx 0.24$ at the peak value (not shown). It is worth mentioning that the high demagnetizing factor of the film leads to vortex penetration at low applied fields, relaxing the demagnetizing factor. This result then suggests that the dc field broadening of χ_{ac} in the Nb film as compared to the porous film is related to higher pinning provided by antidots. This effect becomes more obvious observing that the superconducting transition in Nb_P is narrower at $H = 2000$ Oe than at lower dc fields (1450 Oe).

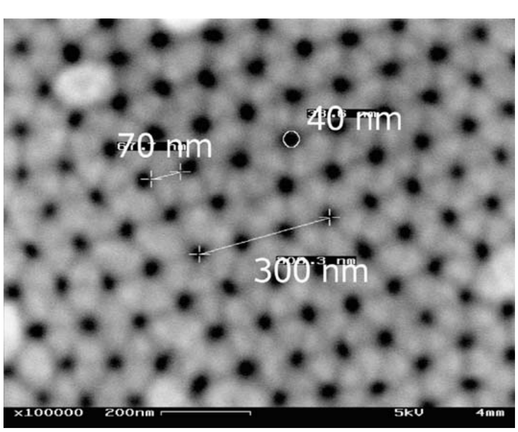

Fig. 1. SEM image of the 100 nm thick porous Nb film. Distance between pores $D = 100$ nm, pore diameter $d = 40$ nm, width of superconducting stripe between pores is $\sim$60 nm.

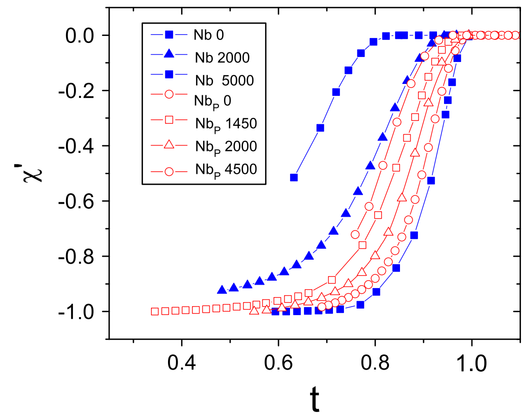

Fig. 2. $\chi_{ac}(T)$ for the continuous Nb film, Nb (full symbols), and for the porous Nb film, Nb_P (open symbols), as a function of reduced temperature $t = T/T_{C0}$, for different values of applied H.

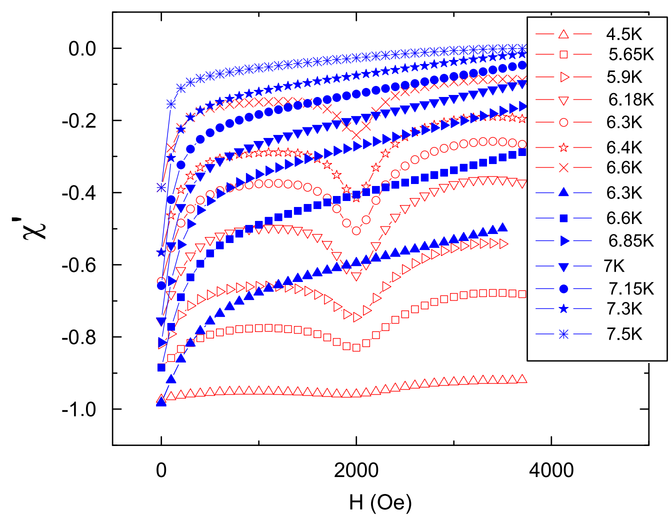

Fig. 3. $\chi_{ac}(H)$ (ZFC) for both samples at different temperatures, Nb (full) and Nb_P sample (open symbols). Nb_P sample shows matching effects for $H_1 = 2000$ Oe.

Fig. 3 shows $\chi_{ac}(H)$ for both samples at different temperatures. In all cases, the samples were cooled from the normal state to the target temperature in zero field (ZFC). Full symbols are for the Nb film, while open symbols are for Nb_P sample. In the second case, matching effects are clearly observed at $N * H_1 = N * (2000 \pm 50)$ Oe, close to the calculated matching field value for an ordered triangular antidot array. As expected, H_1 is not function of temperature.

Critical current density may be obtained from the expression for χ_{ac} for a circular disk in critical state CS in a transverse magnetic field, $\chi'_{ac} = -(1/h)\tanh(h)$ where $h = h_{ac}/H_C(H,T)$ and $J_C(H,T) \propto H_C$. We plot $J_C(H,T)$ in Fig. 4, only for $T = 5.65$ K for the Nb_P film (curve (a)) and for two different temperatures (5.65 and 6.6 K) for the continuous film (curves (b) and (c), as an example. The chosen temperatures show two possible baselines for comparison: if curve (c) is taken as the baseline, the description

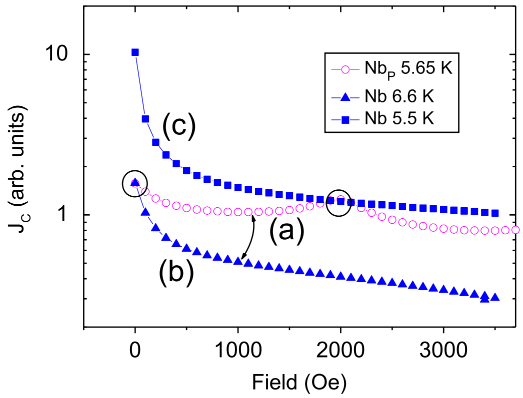

Fig. 4. $J_C(H,T)$ calculated for a circular disk in critical state in a transverse magnetic field from $\chi_{ac}(H,T)$ data, both for the continuous (full) and the porous (open symbols) films. (See text.)

is that the film with antidots has a lower J_C or lower pinning than the continuous film, originated by fluxoid quantization suppression of T_C, except at the matching field H_1 where no additional currents are induced to quantify the fluxoid in each hole. However, this description cannot account for the different critical currents at zero applied field in both samples, and moreover, the compared curves are at different reduced temperatures: $t=0.78$ and 0.67 for the porous and the continuous film, respectively. In contrast, if curve (b) is taken as the baseline, $\chi_{ac}(H=0)$ (and therefore $J_C(H=0)$) consistently coincide for both samples, having both measurements similar reduced temperatures ($t=0.78$ and 0.80 for the porous and the continuous film, respectively). In this case, the result is that antidots provide efficient pinning sites and enhance J_C in the whole field range and almost fourfold at the first matching field for this reduced temperature.

In dc experiments, matching effects are also observed. Fig. 5(a) shows $M(H)$ at different temperatures for the porous sample (data in the fourth quadrant for $T=4.9\,$K has been added for completion as $-M(H)$ of the positive branch for $0<H<1\,$T). In Fig. 5(b) we show results for both samples at the same reduced temperature $t=0.67$. The critical current density for Nb_P is approximately twice the current in the Nb film for $H=H_1$, smaller than the obtained J_C in ac measurements, probably due to relaxation. The large difference at zero field is still an open question.

A rough estimate of the zero temperature coherence length for the Nb_P sample, $\xi(0)\sim 20\,$nm, was obtained from the slope of the $H_{C2}(T)$ curve (not shown), determined from the $M(H)$ curves, $H_{C2}(T)=\phi_0/2\pi\xi^2(T)$ with $\xi(T)=0.74\xi(0)/\sqrt{1-T/T_C}$. Therefore, $\xi(T)$ was not much larger than the superconducting stripes between pores (see Fig. 1) even for the highest measured temperatures, indicating that wire network effects should not be dominant.

We can therefore conclude that the broadening of $\chi_{ac}(T)$ with field for the Nb sample indicates that the porous sample has higher effective pinning and Little and Parks type of effect is not dominant in this range of temperatures. Curves at similar reduced temperature for both samples should be the ones compared. This leads to conclude that the tested antidots are good pinning centers that enhance J_C in a wide range of temperatures.

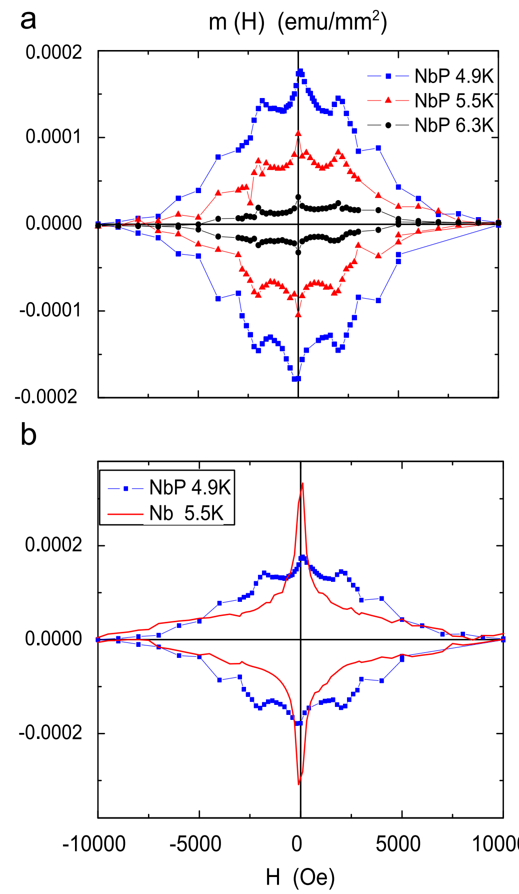

Fig. 5. (a) $M(H)$ at different temperatures for the porous sample where matching effects are observed for $H_1=N*2000\,$Oe. (b) $M(H)$ at $t=0.67$ for Nb_P and Nb films.

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References

[1] A.A. Zhukov, E.T. Filby, P.A.J. de Groot, V.V. Metlushko, B. Ilic Zhukov, Phys. C 404 (2004) 166 (Refs. [1–7]).
[2] A.V. Silhanek, S. Raedts, M. Lange, V.V. Moshchalkov, Phys. Rev. B 67 (2003) 64502.
[3] U. Patel, Z.L. Xiao, J. Hua, T. Xu, D. Rosenmann, V. Novosad, J. Pearson, U. Welp, W.K. Kwok, G.W. Crabtree, Phys. Rev. B 76 (2007) 020508(R).
[4] A. Buzdin, D. Feinberg, Phys. C 256 (1996) 303;
A.I. Buzdin, Phys. Rev. B 47 (1993) 11416.
[5] B. Pannetier, J. Chaussy, R. Rammal, Phys. Rev. Lett. 53 (1984) 1845.
[6] W.A. Little, R.D. Parks, Phys. Rev. Lett. 9 (1962) 9.
[7] U. Welp, Z.L. Xiao, J.S. Jiang, V.K. Vlasko-Vlasov, S.D. Bader, G.W. Crabtree, J. Liang, H. Chik, J.M. Xu, Phys. Rev. B 66 (2002) 212507.
[8] E. Rosseel, T. Puig, M. Baert, M.J. Van Bael, V.V. Moshchalkov, Y. Bruynseraede, Phys. C 282 (1997) 1567.
[9] C.-P. Li, I.V. Roshchin, X. Batlle, M. Viret, J. Appl. Phys. 100 (2006) 074318.